Understanding the Global Distribution of Monsoon Depressions

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LONG-TERM GOALS

This project aims to improve the understanding of cyclonic storms called monsoon depressions, which play an important role in the meteorology of the tropical and subtropical eastern hemisphere and serve as precursors for typhoons in the Indian and Western Pacific Oceans. This work serves as part of a broader effort to better understand and predict tropical cyclogenesis and the variability of monsoons.

OBJECTIVES

Synoptic low pressure systems embedded in continental-scale monsoon circulations play a central role in the meteorology of the tropical Indian and western Pacific oceans during local summer, producing a large fraction of rainfall in the Indian and Australian monsoons and enhanced surface wind variability over oceans (Yoon and Chen, 2005; Goswami et al., 2003; Davidson and Holland, 1987). The more intense occurrences of these low pressure systems are called monsoon depressions, which produce 10-20 cm/day of precipitation and frequently evolve into typhoons. Despite the importance of these low pressure systems, the mechanisms responsible for their formation, intensification, and propagation are not understood (e.g. Beattie and Elsberry, 2010). Furthermore, no climatology of these storms exists for regions outside of India.

This project aims to:

- document the global frequency and geographic distribution of monsoon depressions,
- determine which environmental parameters (e.g. wind shear, sea surface temperature) control genesis of monsoon depressions,
- examine how the dynamical structure of monsoon depressions varies regionally and throughout the storm life cycle, and
- assess and further develop theories for storm formation and structure.

APPROACH

This study builds understanding of the dynamics of monsoon depressions through three main tasks. In the first task, a database of observed monsoon depression tracks is constructed, as only some of these storms are included in existing best-track archives of tropical cyclones. In the second task, a genesis

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potential index used for tropical cyclones is objectively adapted to monsoon depressions, providing a statistical description of the association of depression occurrence with environmental parameters such as wind shear and humidity. The third task examines the dynamical structure and evolution of monsoon depressions using idealized cloud-system resolving models together with observational composites based on the climatology compiled in the first phase of the project.

Key individuals are:

- William Boos (PI), Assistant Professor at Yale University, directs the project work flow and supervises other personnel. He is performing observational analyses and developing theory.
- John Hurley, postdoctoral associate at Yale University, is compiling the depression climatology and producing observational composites.
- Varun Murthy, second-year doctoral student at Yale University, is performing cloud-resolving model studies of monsoon depressions in idealized domains.
- Sarah Ditchek, undergraduate intern at Yale University, is adapting existing genesis potential indices to monsoon depressions.

WORK COMPLETED

The following tasks have been completed since the start of this work in June 2011:

1. Depression climatology: An automated feature tracking algorithm [based on the TRACK program of Hodges (1995)] was used to identify the locations and horizontal trajectories of cyclonic relative vorticity maxima in the global ERA-Interim reanalysis for 1979-2012. An existing monsoon depression climatology for India (Sikka 2006) compares well with our results in the Indian domain, lending confidence to our results.

2. Genesis potential index: We developed a genesis potential index for Indian monsoon depressions, using both Poisson regression (Tippett et al. 2011) and logistic regression methodologies. These indices are currently being fine tuned.

3. Observationally based dynamical studies: The dynamical structure of monsoon depressions has been examined in composites and case studies, and compared to existing theories for depression growth and propagation.

4. Idealized model study: We conducted boundary-forced integrations of the Weather Research and Forecast (WRF) model in a continental-scale domain in an attempt to simulate the spontaneous emergence of monsoon depressions. However, simulated structures were not realistic, probably because this model used parameterized convection. We are now performing initial-condition runs with the WRF model using explicit convection (i.e. a cloud-system resolving model) to study the mechanisms of growth and propagation of an initial seed vortex.

RESULTS

Several notable results have been obtained and are in the process of being incorporated into manuscripts that will be submitted to refereed journals within the next 3-6 months:

1. **The climatology of monsoon low pressure systems reveals the geographic and temporal distributions of storms categorized by intensity.** Weak storms (lows) are much more abundant than strong storms (depressions and deep depressions; Fig. 1). The Sahara desert is the most active source region on Earth for monsoon low pressure systems, but most of these disturbances are short-lived, non-precipitating, and confined to the lower troposphere. The weak Sahara storms exhibit a pronounced seasonal cycle with a maximum in August, in contrast to the more intense West African storms which have less seasonal variation (Fig. 2). The most intense storms (deep depressions and stronger) are generated almost entirely over ocean, while storms of intermediate strength (depressions) originate over both land and ocean. Monsoon depressions in India are roughly equal in number to depressions in West Africa (where they are typically called African Easterly Waves). Interannual variability in the number of low pressure systems is relatively low in each region, with peak-to-trough variations in annual counts being less than half of the average annual count.
2. **Composite structures of monsoon depressions are remarkably similar between South Asia, Australia, and the West Pacific.** Storms in these regions have a cold core at low levels and a warm core in the middle to upper troposphere. This thermal structure is associated with a potential vorticity (PV) maximum in the middle troposphere (Fig. 3). This PV maximum typically lies in the region of time-mean westward flow; since PV is a conserved quantity that can be inverted to obtain winds and temperatures, this indicates that the westward propagation of South Asian monsoon depressions likely results from simple advection. This is a new finding that contrasts sharply with previous hypotheses requiring interaction of precipitating convection with the low-level vorticity field (Sanders 1984, Chen et al. 2005). Calculation of the time tendencies of PV for a case study confirm that the westward propagation is indeed due to adiabatic advection (Fig. 4).
3. **Storm structures are inconsistent with theories of baroclinic growth, the most widespread idea for the mechanism of depression amplification.** PV maxima are localized in space, which precludes dry baroclinic growth, and PV structures are also inconsistent with existing models of moist baroclinic growth. Results suggest that monsoon depressions instead share dynamics with the more general, but incompletely understood, class of tropical depressions.
4. **Genesis of monsoon low pressure systems is strongly associated with high values of vertically integrated atmospheric water vapor and of low-level absolute vorticity.** Statistical analysis of multiple variables typically thought to be involved in tropical cyclogenesis showed weaker associations with vertical wind shear, mid-tropospheric relative humidity, and measures of convective available potential energy (CAPE).

IMPACT/APPLICATIONS

Weather and climate model development: The results of this project will allow model simulations of weather in monsoon regions (e.g. the Indian Ocean) to be assessed using observed vortex distributions. The finding that monsoon depressions are mid-tropospheric PV maxima indicates that the fidelity of model convection will be crucial for properly simulating the structure of monsoon depressions. In contrast, given a correct structure, propagation should be easy to simulate since it depends only on adiabatic advection.

Prediction on synoptic time scales: Studies of model skill for monsoon depression forecasting have mostly proceeded empirically, with previous authors finding sensitivity of skill to model resolution, convective physics, and initial conditions (e.g. Routray et al., 2010). Greater theoretical understanding of the mechanisms governing monsoon depressions may thus guide the improvement of forecast models. The genesis potential index developed by this study may also be useful in synoptic forecasting, providing understanding of how large-scale parameters influence depression occurrence.

Tropical cyclogenesis: Monsoon depressions serve as precursors for tropical cyclones (e.g. McBride and Keenan, 1982). An improved understanding of monsoon depression dynamics is thus expected to contribute to our theoretical understanding of tropical cyclogenesis.

Response to climate shifts: Synoptic activity and extreme rain events in the Indian summer monsoon have increased since the 1950s, but this increase is associated with enhanced activity of weaker low pressure systems and a decline in the activity of more intense systems (e.g. Ajayamohan et al., 2010). The genesis potential index developed in this project is expected to be useful in understanding how future variations in climate might influence depression activity in the broader Asia-Pacific region.

RELATED PROJECTS

Interannual variability of monsoons: We have found a statistically significant relation between interannual variations in monsoon precipitation and the equivalent potential temperature of near-surface air over land. This relationship was found to hold in all of Earth's regional monsoons, and is important because it shows that monsoon rainfall is related not only to SST, as emphasized by previous studies, but also to a thermodynamic variable that is defined over land.

Thermodynamic bias of climate model simulations of monsoons: We have shown that almost all climate models participating in the Coupled Model Intercomparison Project (CMIP) exhibit a common bias in the thermodynamic structure of the South Asian summer monsoon that is caused by poor representation of orography. The highly smoothed topography used in these models allows dry air from the deserts of western Asia to penetrate the monsoon thermal maximum, reducing model upper-tropospheric temperatures and suppressing monsoon precipitation.

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Hurley, J. V. and W. R. Boos: Interannual variability of monsoon precipitation and subcloud equivalent potential temperature. *J. Climate* [in press, refereed].

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HONORS/AWARDS/PRIZES

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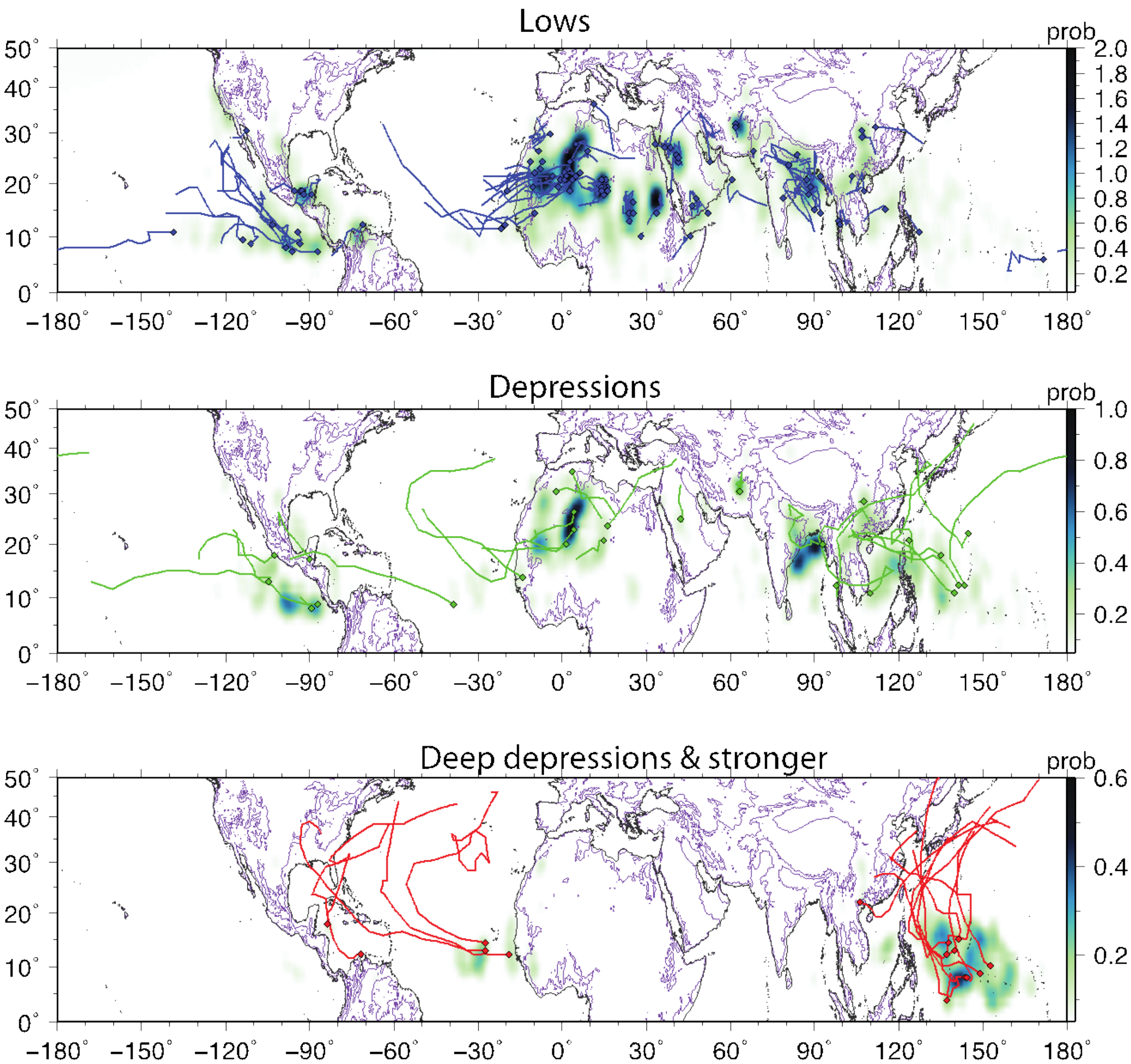

Fig. 1: Frequency of genesis for various storm categories (color shading) for May-Sept. 1979-2012, based on ERA-Interim data. Tracks are shown for the year 2012 only, to illustrate typical characteristics. Tracks are color coded by intensity (lows in blue, depressions in green, and deep depressions and stronger storms in red).

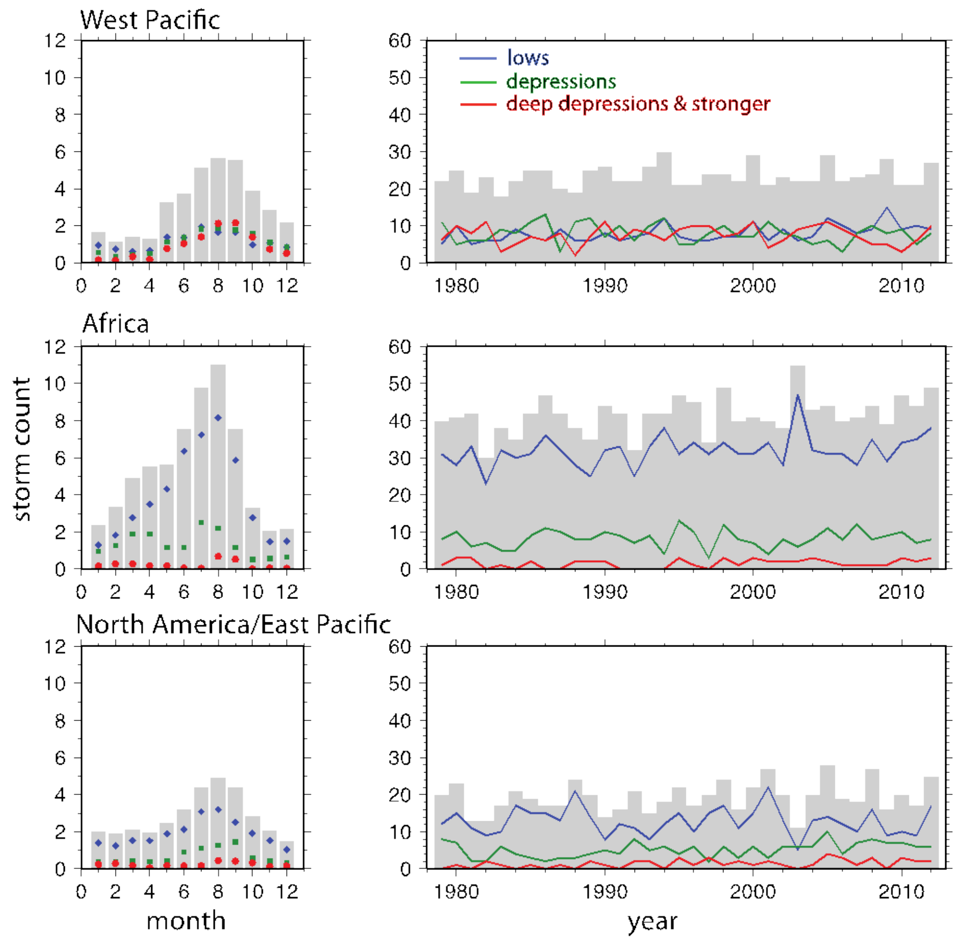

Fig. 2: Time series of storm counts for several regions in the northern hemisphere. Left column shows the climatological mean annual cycle, and right column shows summer storm counts for each year. Gray bars represent the sum of all low pressure systems, while blue, green, and red symbols represent the subsets associated with lows, depressions, and deep depressions, respectively.

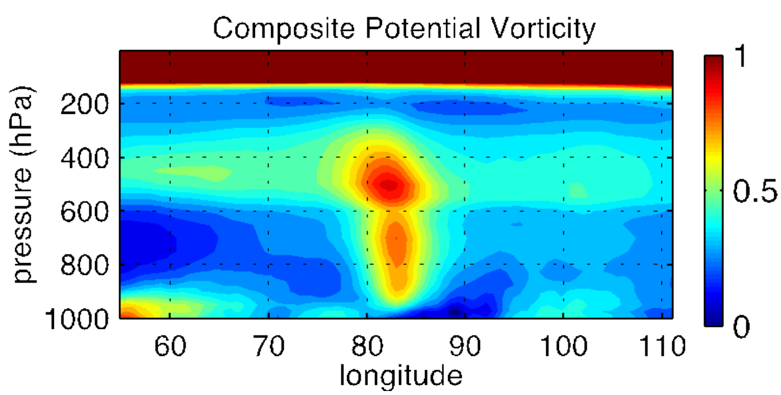

Fig. 3: Composite mean vertical section of Ertel's potential vorticity (PV) for Indian monsoon depressions. Although relative vorticity peaks in the lower troposphere (not shown), PV peaks at 500 hPa.

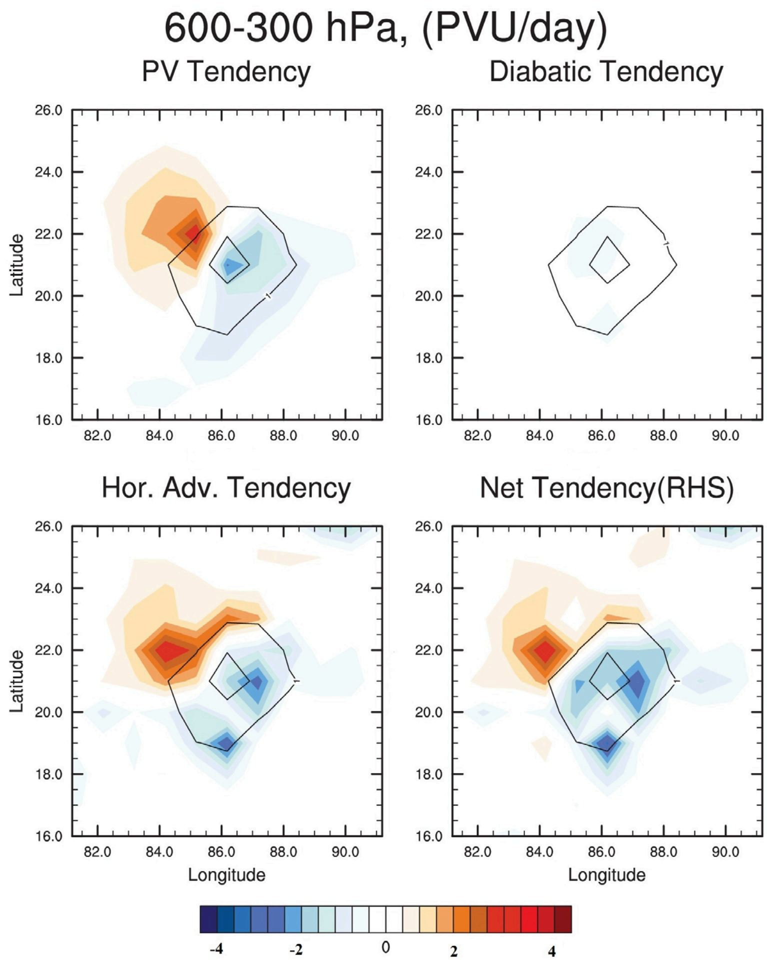

Fig. 4: Latitude-longitude plot of PV tendencies (colors, in PVU/day) for one representative Indian monsoon depression. All quantities are averaged vertically between 600 hPa and 350 hPa, temporally between Sept. 15 and Sept. 18, 2008, and are centered on the storm. The PV (black contours, 1.0 PVU interval) is shown for reference. Top left panel shows the Eulerian rate of change of PV, top right shows the diabatic PV tendency, bottom left shows the horizontal advective tendency, and bottom right shows the sum of the diabatic and total advective tendencies. The vertical advective tendency is not plotted, but is of similar amplitude to the diabatic tendency.